

# **Numerical Studies of Acoustic Particle Velocity and Acoustic Variability with a SSF/PE Model**

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## **LONG-TERM GOALS**

The calculation of underwater acoustic pressure fields using numerical models has been at the core of numerous projects related to both sonar and environmental applications. This varies from simple sonar “range-of-the-day” predictions to the inversion of acoustic data for determination of bottom ocean properties. Although great progress has been made with existing models that compute the acoustic pressure field, much of the previous work has ignored other aspects of the propagation, such as the additional information available in the associated acoustic particle velocity fields, and the impact of environmental uncertainty on sonar predictions. The goal of this 2-year project was to examine these issues and determine how they may be utilized to improve performance for a variety of applications.

## **OBJECTIVES**

The objectives met for the first year’s effort were to expand existing modeling capabilities to (1) provide calculations of the unique characteristics of the acoustic particle velocity field, (2) directly compare this with analytical predictions, (3) examine the field behavior in range-dependent environments, and (4) investigate properties of the vector fields on basic signal processing algorithms. Calculations of acoustic particle velocity were made in generic ocean environments in an attempt to understand what features of the particle velocity field may be unique and exploitable. By developing intuition on the nature of the velocity field, new algorithms for array processing and exploitation of environmental variability were developed.

Much of the second year’s effort was conducted while on sabbatical at NUWC-Newport (Oct ’05 through Jan ’06) and the Royal Netherlands Naval College (RNLNC, Feb ’06 through Jul ’06). The time at NUWC included the opportunity to process measured data on an array of vector sensors during calibration runs at Lake Pend Oreille. The objectives of this work were then to substantiate some of the phenomena predicted during the first year’s effort, and test the processing algorithms developed. The time at the RNLNC was spent working with Prof Jean-Pierre Hermand (Univ Libre de Brussels and RNLNC) and his students on inversion algorithms and signal processing approaches. Objectives of this work included the development of routines for incorporating acoustic vector data into the study of oceanographic variability.

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## APPROACH

For this work, a previously developed technique for computing acoustic particle velocities from a PE model,<sup>[1]</sup> implemented in the MMPE model,<sup>[2]</sup> was employed to produce synthetic acoustic vector field data (pressure and particle velocity) in a variety of littoral environments of interest for a range of source parameters. This data was then used to test processing routines for plane-wave beamforming and processing of acoustic intensity.<sup>[3]</sup> Numerical investigations of matched-field processing with vector sensor data was also considered.<sup>[4]</sup> Once the routines were successfully tested, measured data from a NUWC vector sensor line array (VSLA) was processed. Specific phenomena associated with multipath propagation first observed in the model results were also confirmed in the array data.<sup>[5]</sup>

For the variability and inversion studies, I began by studying how the split-step Fourier PE (SSF/PE) approach may be utilized in adjoint methods.<sup>[6]</sup> This led to discussions with colleagues at ULB and RNLNC on methods for incorporating particle velocity data into adjoint methods and inversions based on metaheuristic approaches.<sup>[7,8]</sup> Additional work also considered novel beam patterns for vector sensors.<sup>[9,10]</sup>

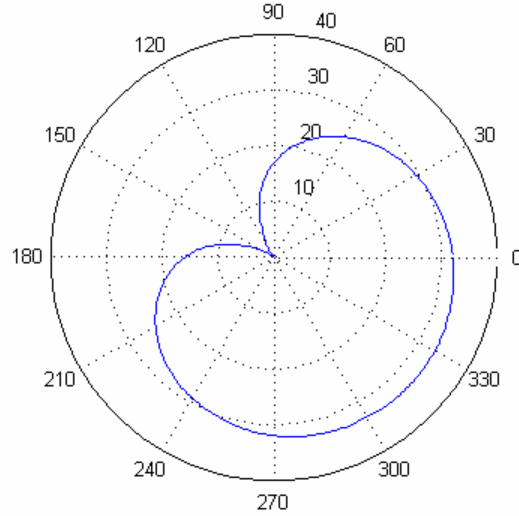
## WORK COMPLETED

The theoretical development of the PE model approach to computing complex particle velocity fields was completed and incorporated into the MMPE model in FY05. PE calculations were then used to show the influence of bandwidth and multipath resolution on arrival angle determination. Basic beamforming analysis was employed to illustrate the fundamental nature of the velocity field for determining direction of energy flow. Analysis of local directional intensity was also examined in the context of multipath interference. Basic (linear) matched-field processing of vector data for source localization was also examined. These processing approaches were applied to measured data from the calibration tests of NUWC's vector sensor line array. For beamforming the measured acoustic vector data, proper calibration of the array elements was required. Additionally, new vector sensor element steering patterns were investigated. Work was also initiated on using vector data in a variety of inversion schemes.

## RESULTS

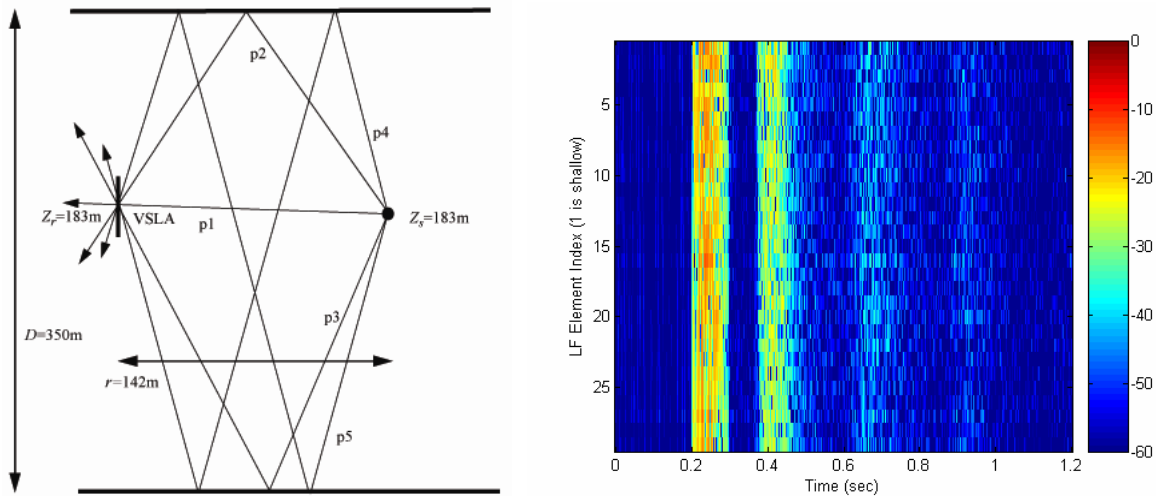
To begin processing the measured acoustic vector data from the NUWC vector sensor line array (VSLA), it was necessary to first insure proper calibration of the data. Previous analysis by NUWC researchers showed that the relative orientation of the various vector sensors remained fixed within the array, and could be accounted for with pre-processing. To combine the pressure signals with the acceleration data to form cardioids, however, required additional processing. First, acceleration data was transformed to velocity data over the band of interest (500 – 1800 Hz). Second, the relative scaling between pressure and velocity was not the theoretical value of acoustic impedance ( $\rho c$ ), but was an arbitrary value that had to be determined by trial and error.

This calibration was performed with a CW tone (1 kHz) and the VSLA deployment in a vertically moored geometry. The direction to the source was determined to be approximately  $3.1^\circ$  below the center of the array axis, and at  $315^\circ$  relative to the azimuthal orientation of the sensors. With the proper relative scaling of the pressure and velocity, the traditional cardioid pattern of vector sensors was achieved with a deep null in excess of 33 dB down, as shown in Fig. 1.



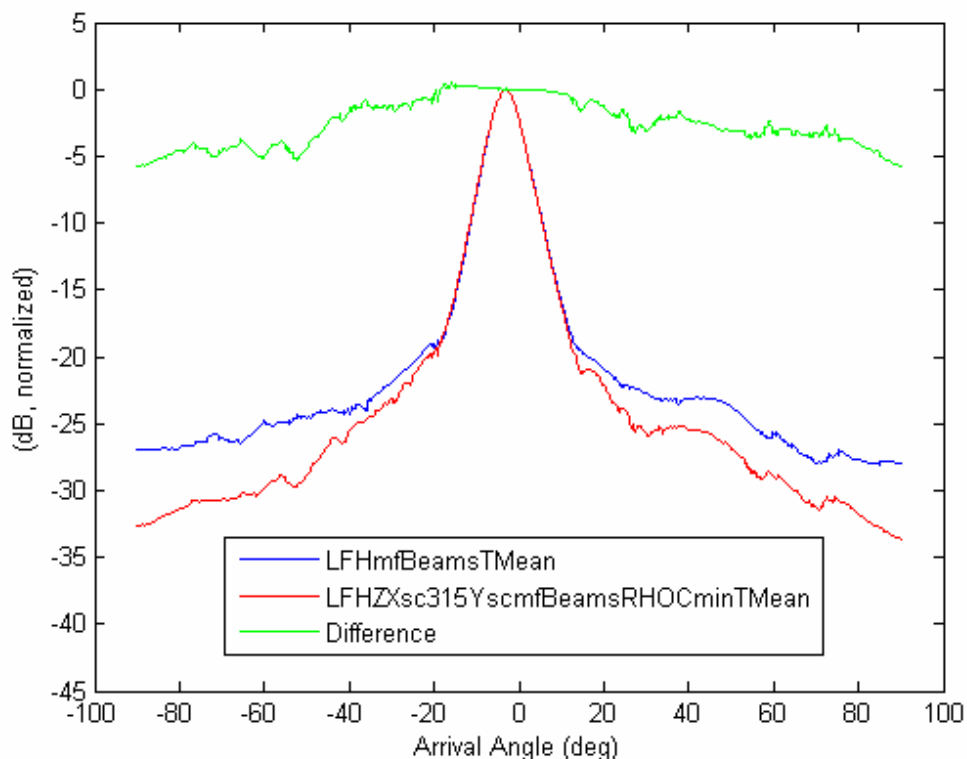
**Figure 1: 2-D slide through cardioid beam pattern for vector sensor computed using 1 kHz source along axis of main lobe. Proper scaling of pressure and velocity signals is found to produce deep null in excess of 33 dB in opposite direction of main lobe.**

The subsequent analysis of VSLA data focused on multipath effects during vertical calibration runs. This included both CW (1 kHz) and LFM chirp (300 msec centered at 1.15 kHz) signals. The geometry of the propagation paths between source and VSLA is depicted in Fig. 2, which displays one of the LFM transmissions. The arrival angles and travel times for the five paths illustrated are as follows:  $\phi_1 \approx 0^\circ$ ,  $t_1 \approx 95$  msec,  $\phi_2 \approx -\phi_3 \approx 70^\circ$ ,  $t_2 \approx t_3 \approx 250$  msec,  $\phi_4 = -\phi_5 \approx -80^\circ$ , and  $t_4 = t_5 \approx 480$  msec.



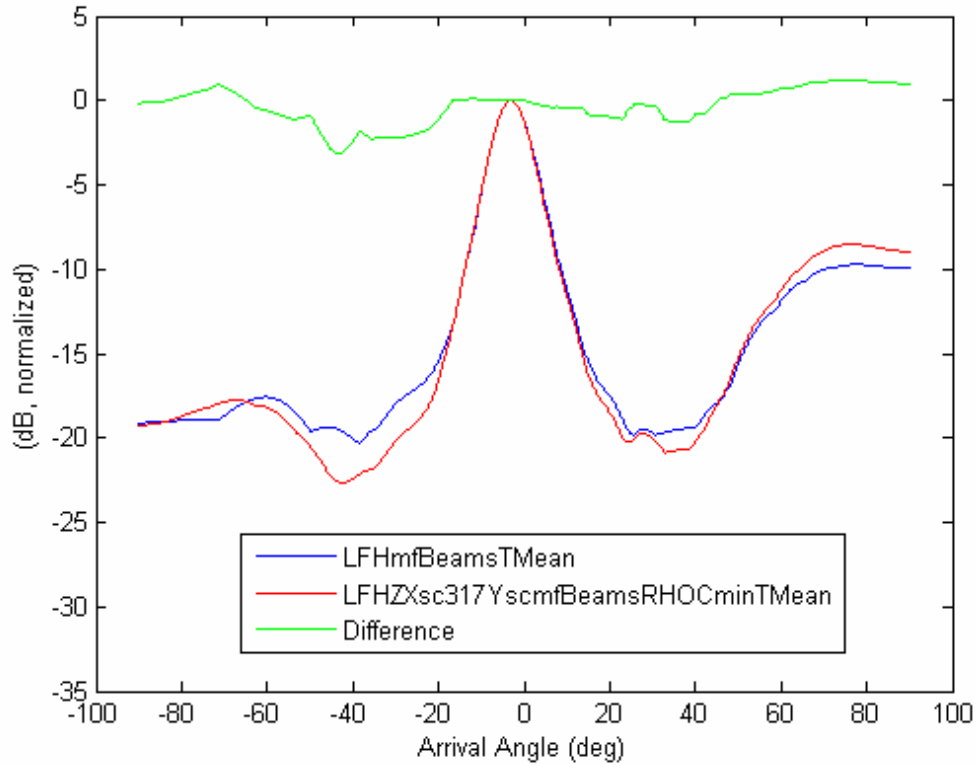
**Figure 2: Geometry of propagation for vertical calibration tests (left), and the arrival structure due to LFM chirp transmission (right).**

In Fig. 3, the results of beamforming the match-filtered first arrival of the LFM chirp are displayed. The data displayed also includes a 20 msec mean to reduce signal fluctuations. Both pressure-only and vector (pressure plus velocity) data were processed and are compared in the figure. The dB difference between the two is also plotted, which shows improvement in sidelobe rejection of up to ~5dB.



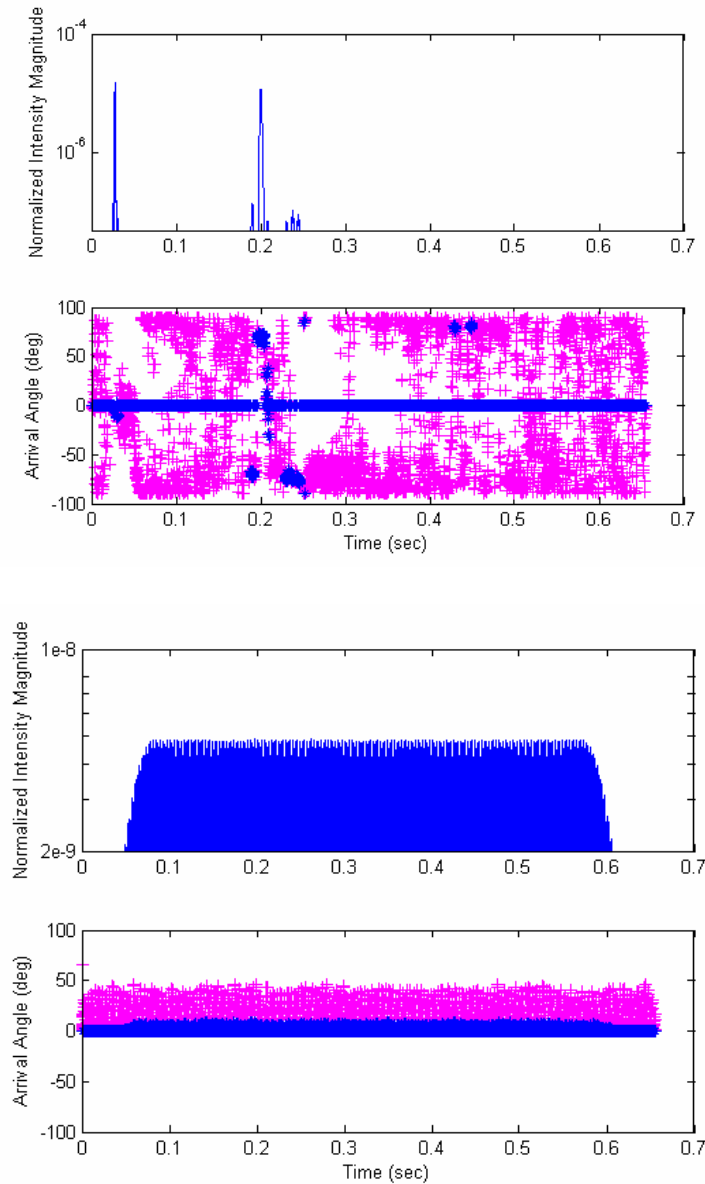
**Figure 3: Plots of beamformed, match-filtered first arrival of LFM chirp. Blue curve shows standard, pressure-only processing while red curve shows vector data processing (both normalized to zero dB peak). Green curve shows dB difference, displaying sidelobe suppression of nearly 5 dB.**

In Fig. 4, similar results are displayed for the CW signal. As before, a 20 msec mean is computed for both pressure-only and vector data, and the results are compared. In this case, the gains are much less significant with less than 3 dB enhancement near the main arrival direction, and slightly negative (~1 dB worse performance) in directions associated with multipath arrivals.



**Figure 4: Plots of beamformed CW signal. Blue curve shows standard, pressure-only processing while red curve shows vector data processing (both normalized to zero dB peak). Green curve shows dB difference, displaying sidelobe suppression of less than 3 dB near dominant arrival but reduced performance near multipath arrivals.**

The negative impact of multipaths was also observed when processing directional intensity data. Specifically, the ratio of the components of the real, instantaneous intensity was computed when the signal intensity crossed some threshold. In Fig. 5, the results of a simple algorithm that computed this ratio are displayed for both the LFM chirp (left) and CW signals (right). The upper figures show the signal intensity magnitude that crosses the threshold, while the lower figures show the angle determined from the intensity component ratios (both with and without the threshold). Additionally, the data has been averaged over 10 sensors to smooth some of the fluctuations.



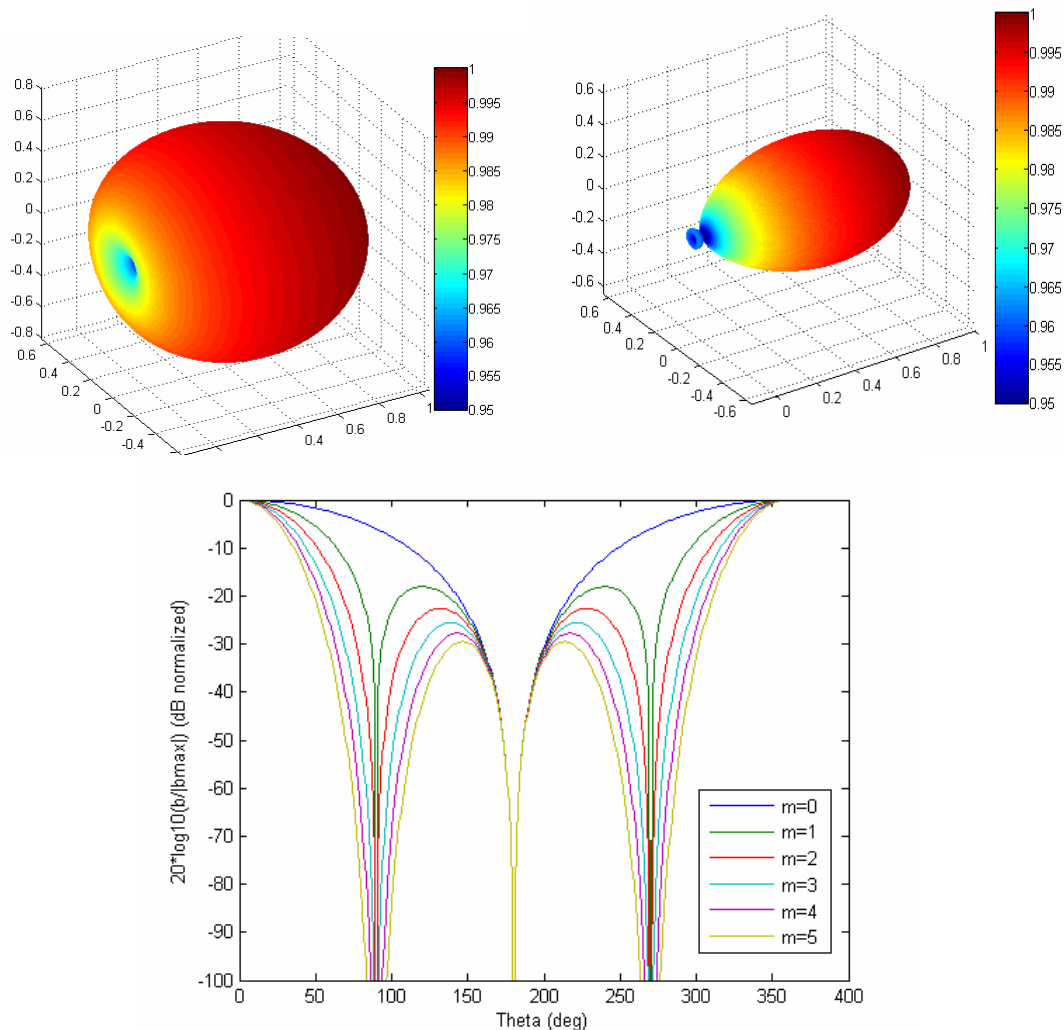
**Figure 5: Ratio of real parts of vertical to horizontal components of mode 5 vector velocity to determine angles of particle motion in the field.**

These results are consistent with previous predictions of multipath influences and degradation of vector sensor array performance.<sup>[3]</sup> However, it is important to recognize that these degradations are due, in part, to the simplifying assumptions inherent in standard, linear, plane-wave processing. More sophisticated processing techniques that do not make such assumptions and attempt to account for the multipath structure may be more robust. Some initial attempts<sup>[4]</sup> at employing linear matched-field processing techniques showed modest gains with vector sensor data, but were rather inconclusive. Further work is necessary to examine this approach more closely.

In addition to the simplifying assumptions of plane-wave beamforming was the use of basic cardioid steering patterns for each vector sensor element. More recently, new steering patterns for vector sensors have been investigated. These steering patterns are non-linear but non-adaptive, and defined in terms of products between cardioids and various orders of hippopedes. The patterns, dubbed

“hippioids”, have better angular resolution in the forward direction while maintaining the same deep null in the backward direction. Figure 6 provides a sample comparison of the standard cardioid steering pattern and 2nd order hippoid. Comparisons of other orders along the axis of symmetry are also provided.

These new steering patterns have been tested on 2-D vector data taken from DIFAR buoys.<sup>[9,10]</sup> The results show noticeable improvements in the sensor’s ability to extract specific signals of interest that were unobservable when a standard (2-D) cardioid pattern was employed.



**Figure 6: Comparisons of vector sensor steering patterns. Upper left shows 3-D image of standard cardioid pattern, while upper right show 3-D image of 2nd order “hippoid”. Lower plot compares steering patterns along axis of symmetry between cardioid and various orders of hippoids.**



## **IMPACT/APPLICATIONS**

In this work, a successful model for computing acoustic vector field quantities in range-dependent environments was generated. This provides a model for future, numerical investigations into features of the field and how it may be utilized/exploited in various sonar applications (e.g., acoustic comms, barrier detection, etc). It was also shown how the multipath interferers complicate the vector field, and how an array of vector sensors are still required to resolve angles of energy propagation. This was confirmed with processing of real data. These results suggest the need for careful processing of vector sensor data, and the avoidance of over-simplification of their signal response.

The processing algorithms developed will be utilized in future data processing of the NUWC vector sensor line arrays. Development of other sensor element steering patterns, adaptive array processing, and general matched-field processing are also being pursued.

## **RELATED PROJECTS**

Work on the processing of acoustic vector field data is also being carried out by Gerald D'Spain (MPL/SIO/UCSD) and numerous colleagues at NUWC-Newport, among others. New inversion algorithms that incorporate vector sensor data are also being co-developed with colleagues at the Royal Netherlands Naval College.

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